Nucleon Structure Functions and Nuclear DIS

Alexander Molochkov

Institut für Theoretische Physik, Justus-Liebig Universität, Giessen, Germany
Far Eastern National University, Vladivostok, Russia

Abstract. The nucleon structure study in nuclear deep inelastic scattering is considered. It is shown that nuclear data provide a new source of information about dynamics of parton distributions in the nucleon. An exmple of the neutron structure function extraction from the deuteron and proton data is considered. The limit $x \to 1$ of the neutron to proton structure functions ratio is studied. A link between the deep inelastic scattering off the nucleon at high x and elastic scattering off nuclei in high Q^2 region is discussed.

NUCLEON STRUCTURE CHANGE IN NUCLEI

The nuclear data is one of the important sources of information about nucleon structure. First of all, it is connected with absence of a free neutron target for deep inelastic scattering (DIS) experiments, what makes nuclear data the only source of information about neutron structure functions. Another important advantage of the nuclear DIS is access to the kinematic region of large Bjorken x that is unreachable in DIS off the nucleon. For example, the average nuclear Bjorken x ($x_A = 1/A$) corresponds to the very large nucleon x ($x_{\rm N} = M_A/m_{\rm N} x_A \simeq 1$). However, such study cannot be performed without consistent separation of the nuclear and nucleon hard structure. The European Muon Collaboration demonstrated in the nuclear DIS experiments that connection between the nuclear and nucleon hard structure cannot be trivially explained by the Fermi-motion of bound nucleons [1], what was called the EMC-effect. Study of the A-dependence of the effect [2] and nuclear Drell-Yan scattering [3] together with the theoretical investigations performed within the QMC [4] and Chiral soliton [5] models show that the EMC-effect cannot be understood without introducing nucleon structure change in nuclei, which is strongly model dependent. Recently, the nuclear effects in DIS were studied within a fully covariant approach [6] based on the Bethe-Salpeter equation. In the paper [7] it was found that the EMC-effect results from the Fermi-motion of the bound nucleon in the four-dimensional space, which leads to the space- and time-smearing of the bound nucleon. The time-smearing leads to increase of the nucleon localization radius in the four-dimensional space, what corresponds to the explanation of the effect provided by the Q^2–rescaling model [8]. In a 3D projection of the relativistic Fermi-motion the time-smearing of the bound nucleon reduces to the dynamical distortions of the nucleon structure, which correspond to the nucleon structure change obtained within the QMC [4] and Chiral soliton models [5].

Consistent analytical calculations within this approach in the approximations of high Q^2 and small binding energy give the following expression for the nuclear structure

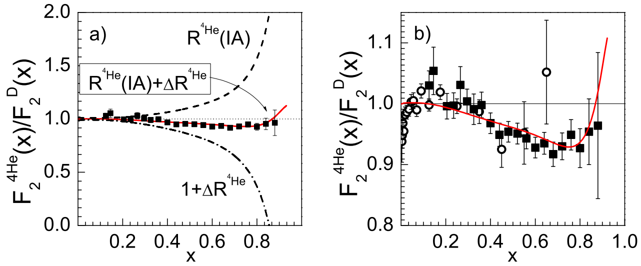


FIGURE 1. Contribution of the impulse approximation (dashed curve $R^{^4He}(IA)$) and nucleon structure function derivative (dashed-dot curve $\Delta R^{^4He}$) to the ratio of the ^{4}He and D structure functions. The experimental values are shown by the dark squares [2].

function:

$$F_2^A(x) = \int \frac{d^3p}{(2\pi)^3} \left[\frac{M_A - E_{A-1} - p_3}{E_\mathrm{N}} F_2^\mathrm{N}(x_\mathrm{N}) - \frac{\Delta_A^\mathrm{N}}{E_\mathrm{N}} x_\mathrm{N} \frac{dF_2^\mathrm{N}(x_\mathrm{N})}{dx_\mathrm{N}} \right] \frac{f^{\mathrm{N}/A}(M_A, \mathbf{p})}{8 M_A E_\mathrm{N} E_{A-1} \Delta_A^{\mathrm{N}\,2}}, \quad (1)$$

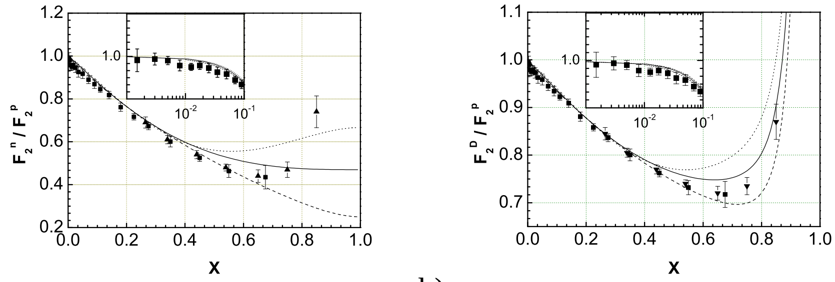
where $f^{\mathrm{N}/A}(M_A, \mathbf{p})$ is a function defined by the solutions of the Bethe-Salpeter equation, E_N is the nucleon on-shell energy, $\Delta_A^\mathrm{N} = M_A - E_\mathrm{N} - E_{A-1} \simeq -T_{kin} + \varepsilon$ is the nucleon energy change due to the Fermi motion ($T_{kin} > 0$ – kinetic energy of the Fermi motion) and binding ($\varepsilon < 0$ – binding energy of the nucleon).

Numerical calculations of the contributions of the different terms in Eq.(1) to the ratio $R^{^4\mathrm{He}} = 2\sigma^{^4\mathrm{He}}/(A\sigma^\mathrm{D}) = F_2^{^4\mathrm{He}}/F_2^\mathrm{D}$ are presented at Fig.1 a). The first term ($R^{^4\mathrm{He}}(IA)$), which results from the Fermi motion in 3D-space, is presented by the monotone increasing dashed curve. The second term ($\Delta R^{^4\mathrm{He}}$) depicted by the point-dashed curve results from the time-smearing of the bound nucleon. Since $M_A < E_\mathrm{N} + E_{A-1}$ and $F_2^\mathrm{N}(x_\mathrm{N})/dx_\mathrm{N} < 0$ this term puts the ratio $R^{^4\mathrm{He}}$ bellow unity in the middle x region and, therefore, produces the EMC-effect resulted from cancellation of the two large contributions. This result is presented by the solid curve, which fits to the experimental data within the experimental errors with rather good accuracy (see Fig.1 b)). Due to the contribution of $dF_2^\mathrm{N}(x)/dx$ the expression (1) establishes a connection between the nuclear data and dynamics of parton distributions in the nucleon expressed by the nucleon structure function derivative.

It is worth noting that according to (1) the functional behavior of the EMC-ratio is defined by the nucleon structure function properties, since then the duality observed in F_2^N can lead to the dual behavior of the R^A in the kinematic region of high and low Q^2. This conclusion is consistent with the experimental results obtained recently in [9].

NEUTRON STRUCTURE FUNCTION

Let's consider Eq.(1) as an integral equation with the unknown function F_2^n. The functions F_2^p and F_2^D are defined by the existing experimental data. The boundary conditions



a) b)

FIGURE 2. Comparison of the obtained $F_2^{\mathrm{n}}(x)$ with experimental data for the a) $F_2^{\mathrm{n}}/F_2^{\mathrm{p}}$ and b) $F_2^{\mathrm{D}}/F_2^{\mathrm{p}}$ ratios. Experimental data are taken from SLAC (triangles) and NMC (squares).

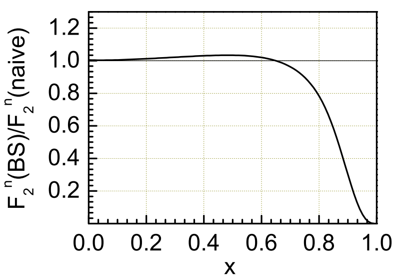


FIGURE 3. The ratio of the $F_2^{\mathrm{n}}(x)$ extracted within the present approach to the naive approximation $F_2^{\mathrm{n}}(x) = 2F_2^{\mathrm{D}}(x) - F_2^{\mathrm{p}}(x)$.

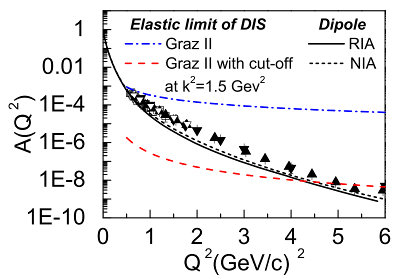


FIGURE 4. Comparison of the elastic limit of $F_2^{\mathrm{D}}(x,Q^2)$ $(x = 2)$with the deuteron structure function $A(Q^2)$.

for the equation are fixed with the help of asymptotics of the nucleon structure functions at $x = 0$ and $x = 1$. Introducing the neutron structure function $F_2^{\mathrm{n}}(x)$ as follows:

$$F_2^{\mathrm{n}}(x,Q^2) = r^{\mathrm{n/p}}(x)F_2^{\mathrm{p}}(x,Q^2); \quad r^{\mathrm{n/p}}(x) = a_1(1-x)^{\alpha_1} + a_2x^{\alpha_2} + b_1x^{\beta_1}(1-x)^{\beta_2}(1+c_1x^{\gamma_1}), \tag{2}$$

we fix the parameters a_1, a_2, α_1, b_1, β_2 by the boundary conditions. According to the limit $F_2^{\mathrm{p}}(0) = F_2^{\mathrm{n}}(0)$, the parameter $a_1 = 1$. The parameter a_2 is fixed according to $lim_{x\to 1}F_2^{\mathrm{n}}(x)/F_2^{\mathrm{p}}(x)$, which is model dependent. We study the three limits predicted by the following three different models. The quark model with SU(6) symmetry gives $r^{\mathrm{n/p}}_{x=1} = 2/3$. The elastic limit gives $r^{\mathrm{n/p}}_{x=1} = \sigma^{\mathrm{n}}_{\mathrm{elastic}}/\sigma^{\mathrm{p}}_{\mathrm{elastic}} \simeq 0.47$. The minimal value of the ratio has been predicted by the model with SU(6) symmetry breaking with scalar diquark dominance — $r^{\mathrm{n/p}}_{x=1} = 1/4$. Assuming same asymptotic behavior for $F_2^{\mathrm{p}}(x)$ and $F_2^{\mathrm{n}}(x)$ at the limit $x \to 1$: $\lim_{x\to 1} F_2^{\mathrm{p}}(x) \simeq C_{\mathrm{p}}(1-x)^3$, $\lim_{x\to 1} F_2^{\mathrm{n}}(x) \simeq C_{\mathrm{n}}(1-x)^3$; we get that the derivative of $r^{\mathrm{n/p}}$ at $x = 1$ is zero. It constrains the following parameters of Eq. (2): $\alpha_1 = 1$, $\beta_2 = 1$, $b_1 = (\alpha_2 a_2 - 1)/(1+c_1)$. The remaining four parameters (α_2, β_1, c_1, γ_1) are used to fit Eq. (1) to the data for $F_2^{\mathrm{D}}(x,Q^2)$ in the range $10^{-3} < x < 0.6$ and $0.5GeV^2 < Q^2 < 40GeV^2$. The result of the F_2^{n} extraction is presented at Fig.2 a). The

experimental data are obtained from the ratio $F_2^{\mathrm{D}}/F_2^{\mathrm{p}}$ within the naive approximation that neglect all nuclear effects in the deuteron. Due to the cancellation of the Fermi-motion and time-smearing discussed in the previous section the naive approximation works well up to $x \simeq 0.7$, what explains the good agreement of the obtained here F_2^{n} with the experimental data. This agreement is illustrated on Fig.3, which shows that at $x > 0.7$ the correct accounting of the Fermi motion in 4D space becomes very important.

The obtained nucleon structure function that contains inelastic channels only allows to study contribution of these channels to the elastic lepton scattering off the deuteron. Calculation of the deuteron structure function at the point $x = 2$, which corresponds to the elastic scattering off the deuteron, we get the result presented at the Fig.4. Thus, the nucleon resonances, contribution of which is presented by the dashed curve, can give sizable contribution to the lepton deuteron elastic scattering at high Q^2.

SUMMARY

The nuclear short-range structure can be expressed in terms of the nucleon structure and four-dimensional Fermi motion of the nucleons. The time-smearing broadens the bound nucleon localization area, what lead to the observation of the nucleon structure change in nuclei – EMC-effect. The pattern of the EMC-effect is defined by cancellation of the two large contributions that are the 3D Fermi motion and the time-smearing of the bound nculeons, which are important at the average and large Bjorken x. Due to the time-smearing the nuclear data enable direct access to the information about nucleon structure dynamics expressed by the nucleon structure function derivative, $dF_2^{\mathrm{N}}(x)/dx$, that is difficult to detect in DIS off the nucleon. Better accuracy in $F_2^{\mathrm{D}}/F_2^{\mathrm{p}}$ data at $x \simeq 0.7-0.8$ can give information about the ratio $F_2^{\mathrm{n}}/F_2^{\mathrm{p}}$ at $x \to 1$ (see Fig.2 b)). Study of the elastic limit of F_2^{D} shows that nucleon structure excitations give sizable contribution to lepton deuteron elastic scattering at $Q^2 > 4GeV^2$.

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